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SOIL CREEP DYNAMICS, SOIL MOISTURE AND TEMPERATURE CONDITIONS ON A FORESTED SLOPE IN THE GRANITIC VOSGES MOUNTAINS, FRANCE

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ABSTRACT

Soil creep, soil water tension and soil temperature were monitored at the Schildmatt experimental site over a 7 month period, in order to study the dynamics of creep movements measured with a specially designed strain gauge probe. The limited displacements and the very low signals which had to be measured were taken into account in estimating the uncertainty in measurements. The results obtained emphasize the very discontinuous and highly reversible character of the creep movements and their seasonal nature. Displacements occurred mainly during two events: their size were 10 mm and 2 mm, but the overall displacements for the whole intensive study period (January–July 1985) was only 3 mm. The relationships with soil moisture and temperature conditions indicated that ice segregation and saturated conditions are major influences, but more needs to be known about the way they act on soil creep.

KEY WORDS soil creep; strain gauge probe; intensive monitoring; soil moisture and temperature; Vosges mountains

INTRODUCTION

Soil creep is generally defined as a slow gravity-driven downslope movement of soil and rock debris that occurs without any plane of sliding within the soil profile and that is perceptible only over long periods Sharpe (1938). It is well recognized that creep is a process that is active only during short periods in most cases (Kirkby, 1967; Finlayson, 1985). The main causes have been identified (Davis and Snyder, 1989; Gilbert, 1909) as changes in soil moisture and temperature, soil water freezing and thawing, which act on expansion and contraction resulting in downslope movements, and the biological activity of roots and animals. Creep is one of the geomorphic processes that contribute to the slow morphodynamic evolution of mid-mountain slopes of humid temperate regions, and as such it is taken into account in models of hillslope evolution (Young, 1978a; Culling, 1983; Ahnert 1987).

Most creep studies have attempted to evaluate the mean long-term creep rates, using cumulative methods, such as Young's pits (Young, 1960) or pillars (Jahn and Cielinska, 1974). The published values are the results of long-term measurements, and they range from a few millimetres to a few centimetres per year, depending on regional climate and the type of material (Selby, 1982; Goudie *et al.*, 1985; Fleming and Johnson, 1975; Young, 1978a, 1978b; Jahn, 1989; Lautridou *et al.*, 1992).

The lack of convenient, accurate techniques for continuous monitoring of this very small soil displacement, together with moisture and temperature conditions within soil profiles, has long prevented detailed field studies using a more dynamical approach to this complex process and the influence of its main factors. However, recent technical progress has resulted in the development of probes to monitor the differential movement within the soil profile (Anderson and Finlayson, 1975; Anderson and Cox, 1978; Finlayson, 1981; Mercier & Geissert, 1982; Auzet, 1982). This paper describes the use of a strain gauge probe (Auzet *et al.*,

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1986) to study soil creep dynamics and its relations to soil moisture and temperature conditions over a 10-month intensive measuring period on a forested slope in the Vosges mountains.

THE CREEP PROBE

Description

The strain gauge probe measures soil creep profiles and their evolution with a vertical resolution fine enough for correlation with vertical changes in moisture and temperature in the upper layers of a soil (Auzet, 1985; Auzet *et al.*, 1986). The probe is made of a supple steel blade (thickness $h = 0{\cdot}3$ mm, width 12·7 mm, length 500 mm). Small strain gauges that deliver an electrical signal proportional to their resistance are placed every 50 mm along the two sides of the blade, at the same levels. The probe is inserted into the soil down to a layer assumed to be stable and is assumed to follow lateral differential displacements within the soil profile. Any flexion of the probe at one level results in changes in the resistance of the two corresponding strain gauges. The gauges at each level are connected across a half Wheatstone bridge, so that the changes in temperature are compensated for and the signal is doubled. The relative elongation of the strain gauges $\Delta L/L$, which is proportional to the curvature ρ (m^{-1}) of the probe at the measurement level, is measured using a system that includes the other half of the Wheatstone bridge.

$$\rho = \frac{2}{h}\frac{\Delta L}{L} \tag{1}$$

A switch box allows the connection of each measurement level. Lateral displacements y (m) at each depth z (m) are calculated geometrically upwards from the bottom of the probe, whose anchoring in the formation is assumed to be stable, to the soil surface using a two-step numerical integration of the curvature (Dahlquist and Björck, 1974):

$$\rho(z) = \left(\mathrm{d}^2y/\mathrm{d}z^2\right)[1 + (\mathrm{d}y/\mathrm{d}z)^2]^{-3/2} \tag{2}$$

with the following conditions at the anchoring level:

$$y_0 = y_1 = 0,\ y'_0 = (\mathrm{d}y/\mathrm{d}z)_0 = 0$$

Slopes $y'(z) = dy/dz$ are obtained by integrating the expression

$$\mathrm{d}y'/\mathrm{d}z = \Delta z\left(1 + y'^2\right)^{3/2} = F(z, y') \tag{3}$$

using the Runge-Kutta method. For $i = 1$ to n:

$$y'_i = y'_{i-1} + (k1 + k2)/2 \tag{4}$$

where

$$k1 = \Delta z F(z_{i-1}, y'_{i-1})$$
$$k2 = \Delta z F(z_i, y'_{i-1} + k1)$$

Displacements $y(z)$ are obtained using the Simpson integration formula. For $i = 2$ to n:

$$y_i = y_{i-2} + (y'_{i-2} + 4y'_{i-1} + y')\Delta z/3 \tag{5}$$

where Δz is the constant distance between two measurement levels.

The probe was checked in the laboratory, using special forms designed according to published creep profiles, with good results; and then within a scale model of a homogeneous loamy slope that underwent freeze–thaw cycles (Auzet *et al.*, 1986; Coutard *et al.*, 1988).

Uncertainty estimation

The very small displacements observed in the field and the very low signals measured made it necessary to carefully check the uncertainty in their estimation using this indirect method. The construction of the probe

(particularly its gluing, wiring and insulating) was checked as was the compensation of the temperature effect. The Wheatstone bridge was frequently calibrated so as to eliminate any significant systematic measurement error.

The random component of the measurement error of the whole system was estimated using one series of 50 successive sets of measurements at each probe level in the field. The statistical distribution of the errors at each level was Gaussian, with a standard deviation (s) of about 4 μm m^{-1}. This value is similar to the precision of 6 μm m^{-1} given by the manufacturer of the measuring bridge. The quality of the connections, which are always a very crucial part of a measuring system, were checked in a second series of tests using the same procedure, except that the switch box was disconnected between measurements. In this case, the standard deviations of the errors, which were again Gaussian, were a little larger, with values of about 7 μm m^{-1}.

The integration error associated with the approximate numerical scheme used to integrate the measured curvatures was estimated by simulation. Simple curves with known curvature at each point were reproduced using this scheme and varying the curvature and the number of integration points (Auzet, 1985). The integration errors were small but increased with the number of integration points and the number of inflexion points. For a simple arc of a circle, the integration error increases from the bottom to the upper part; the error of −0·05 mm is maximum at the surface for a probe of 60 cm length with 12 points of measurement and a simulated displacement of 25·3 mm. In the case of a convex–concave curve made of two arcs of a circle, and a probe of 65 cm length with 13 points of measurement, the computation error was higher, with a maximum error of +0·29 mm just above the inflexion point.

The cumulative effect of the measurement errors and the integration errors on the computed displacements was also tested using a Monte-Carlo simulation. The same simple curves and a straight segment were used, but their known curvature at each integration point was affected by a random error. These errors were drawn randomly within a Gaussian distribution with a mean of zero and a standard deviation $s = 9$ μm m^{-1} to maximize the random measurement errors on deformations. This procedure was repeated 100 times to obtain the statistical distribution, the mean and the standard deviation of the resulting errors on the computed displacements. The results showed that error increased with the number of integration points.

Data processing procedure

The results of this error analysis were used to define objective rules for the interpretation and processing of the deformations measured in the field.

1. According to the uncertainty estimation, we considered that the error in the changes in the strain gauge measurement were $\pm 2s\sqrt{2}$ (where s is the maximum observed standard deviation of 7 μm m^{-1}). The change in the deformation at one level between two dates was considered to be significant only if it was greater than $2s\sqrt{2}$, and the relative displacements between two dates were calculated only if the deformations were significant at one or more levels.
2. If this was the case, 100 profiles were generated for both dates using a Monte-Carlo simulation, by affecting measured deformations with measurement errors drawn from a Gaussian distribution with the observed standard deviation s. The mean and confidence interval of the computed displacements were estimated from these 100 profiles, and were used to decide whether the relative displacements were significant or not.
3. As the confidence interval of displacement at the soil surface increases with the number of integration points, the lower levels were not taken into account when they had no significant deformations, and displacements were computed upwards starting from the last stable level.
4. The total displacement over longer periods was evaluated by averaging measured deformations from several successive dates with no significant change, both at the beginning and the end of the period, to smooth out the effect of small random measurement errors.

THE SCHILDMATT EXPERIMENTAL SITE

Site description

The Schildmatt experimental site at Soultzeren (Haut-Rhin) is part of the Petite Fecht research catchment

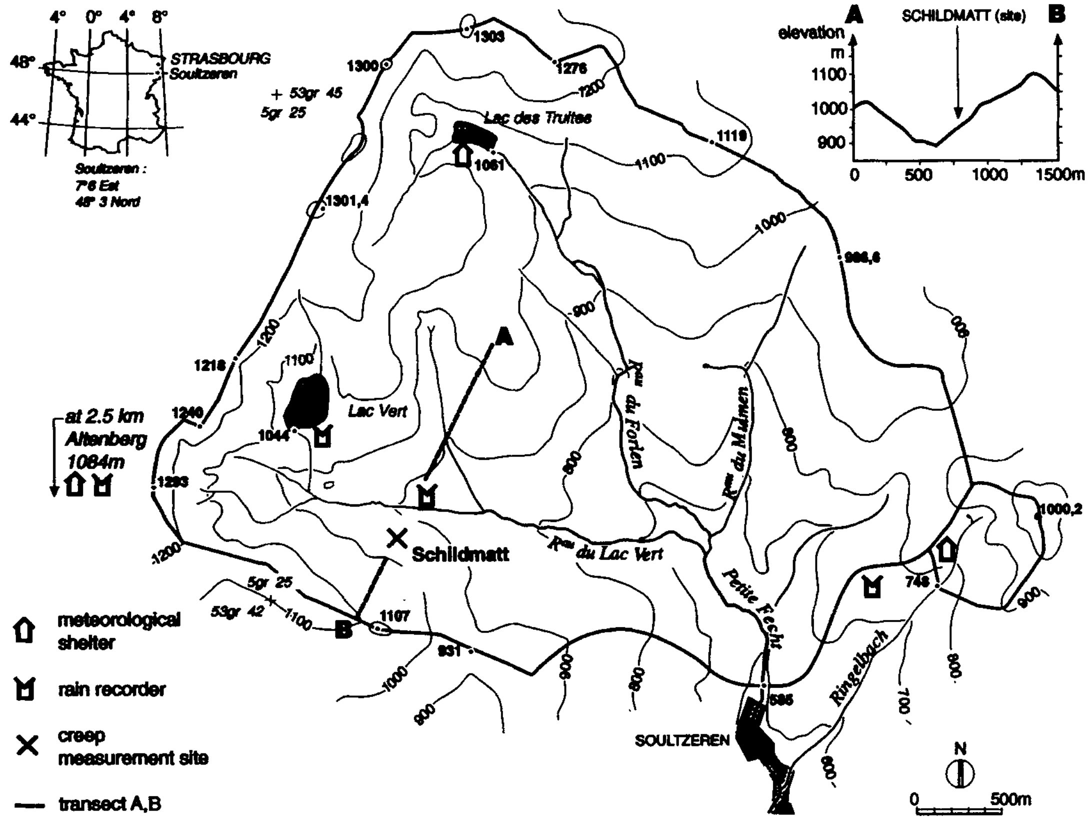

Figure 1. Location of the Schildmatt experimental site and the meteorological station in the Petite Fecht catchment

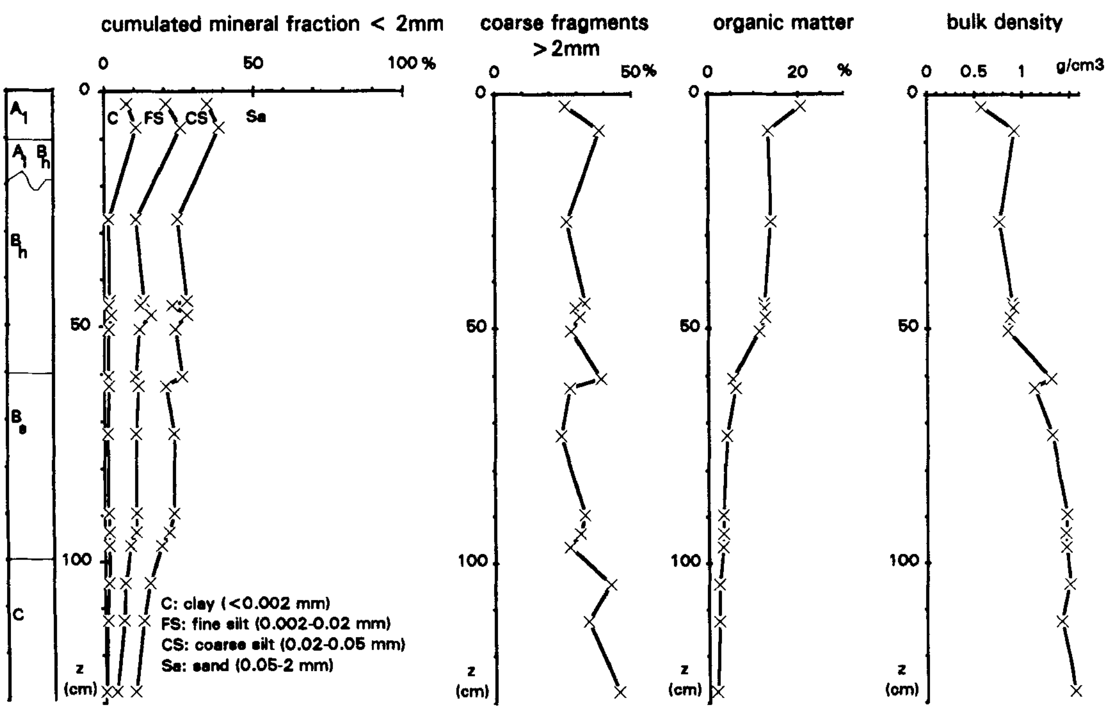

Figure 2. Soil physical characteristics

(Mercier, 1982; Ambroise, 1995), on the east side of the crystalline central Vosges mountains, 70 km SSW of Strasbourg, France. This forested site is located in a 100 year old spruce and fir stand on a north-facing slope, at an elevation of 950 m a.s.l., 200 m above the valley bottom and 1200 m away from the main ridge of the Vosges (Figure 1). The local topography is rather irregular, with a mean slope angle of about 20°. The hillslope was shaped by glacial and periglaxial processes. Its present geomorphic evolution is very slow, mainly due to soil creep and locally uprooted trees.

The periglacial slope formation covering the granite bedrock is 1 m thick at the site. The soil is an acid brown earth with a stony-sandy loam, which belongs to the podzolic series. Figure 2 shows the profile of its main physical and textural properties. The stone content is high, with a coarse (> 2 mm) fraction ranging from 25 to 40 per cent within the soil profile. The organic matter content is high in the upper layers (A_1 and Bh) but decreases rapidly downwards, resulting in large symmetrical variations in the bulk density profile (Figure 2). The litter, which is mainly spruce needles, is 3–7 cm thick. It is frequently water-clogged during snowmelt. The very poor herbaceous layer is discontinuous. There is very little activity of worms and burrowing animals.

The local climatic conditions display high interannual variations and sharp topography-related gradients. The mean annual precipitation exceeds 1500 mm a^{-1} with an interannual standard deviation greater than 300 mm a^{-1}. December is generally the wettest month and April the driest. Mean monthly air temperature ranges from −1°C in January to +15°C in July. Winters without snow are not rare, but during snowy winters the steepness of the valley sides, the northern exposure of the slope and the dense forest cover can result in a long-lasting snow cover, often with a depth of several decimetres. The soil freezes during cold periods once or twice a year, when the soil is not protected by snow cover.

The climatic and morphopedological characteristics of the Schildmatt site are typically the factors causing soil creep in the temperate zone: alternating freezing and thawing, wetting and drying, swelling and shrinkage in A horizons that are rich in organic matter.

Site equipment

The experimental site was equipped to monitor creep within soil profiles, soil moisture and temperature profiles and local climatic conditions (air temperature, precipitation, snow cover) in 1983 and 1984. This equipment was located within an area of about 100 m^2. The strain gauge probe was inserted vertically within the soil profile in November 1984. Measurements were made regularly each week from November 1984 to July 1985 and more frequently during critical periods (large rain event, snowmelt, thaw) and during periods when the strain gauges showed significant change. Because a stabilizing period is needed after disturbing the soil profile by inserting the probe, the measurement period considered in this paper starts in January 1985. Measurements were also made episodically four or five times a year until December 1987. After the winter of 1987–1988, checks on resistances of the strain gauges indicated that the probe had failed in this acid and harsh environment. Creep was also measured using four Anderson tubes (Anderson and Finlayson, 1975) inserted vertically to depths of 150–250 mm in October 1983.

Daily climatic data were available from four meteorological stations surrounding the site at 0·2–4 km and at elevations of 743–1044 m a.s.l. (Figure 1). They provided data on the specific climatic conditions of the study period and its temporal representativeness. In addition, because of rainfall interception by the trees, several rain gauges were placed on the site to measure the rainfall reaching the soil surface. Snow depths were measures along stakes and by soundings.

Soil water tension profiles, which control the direction and intensity of water fluxes, were measured using 31 tensiometers inserted at two places at depths of 2–70 cm within the soil profile. Two sizes of porous cup were used: the smallest cups (diameter 6·3 mm, length 28·6 mm) were inserted horizontally at depths of less than 25 cm, the biggest (diameter 23 mm, length 72 mm) vertically at depths greater than 30 cm.

Soil and air temperatures were recorded every 4 h using 12 carefully calibrated platinum temperature probes. Three probes were at 0, 10 and 100 cm above the surface, two in the litter and seven within the soil profile down to 32 cm, to determine accurately the depth of the freezing and thawing fronts. A maximum–minimum thermometer was used to check the temperature data of a probe placed in a shelter.

RESULTS

Figure 3 shows the climatic conditions during the intensive study period (January 1985–July 1985). The main climatic events were:

(a) two periods of particularly intense, long freezing (24 December–18 January and 10–23 February);
(b) two snowmelts (end of January, and 25–26 March);
(c) two large rain events (30 April–2 May, and 9–10 June).

Table I indicates the displacement measured or computed for different periods and their confidence intervals.

Timing of creep movements

Figure 4 shows the changes in the measured deformation at each level, which indicate when the deformation occurred and at what depth within the soil profile. A positive deviation indicates a downslope curvature, a negative deviation an upslope curvature. When comparing successive dates, sequences of positive (or negative) deviations indicate a continuous change; a return to zero means a stabilization after some displacement, while an alternation of positive and negative deviations means some reversion to the previous form.

Figure 4 reveals the discontinuity of the changes: creep movements occurred only during short periods and were partly reversible. The four upper measurement levels (2–18 cm) showed the highest number of significant events. The levels were indeed in the upper horizons (A1 and A1/Bh), which are the most sensitive to short-term climatic change. The dates with significant deformations correspond well to some climatic events. All levels, except the lowest, showed changes during a period that began on 11 or 18 February, which corresponds to an intense freezing of the soil followed by a thawing in 5 days, assisted by a few milimetres of rainfall. After a relative stabilization in March, several upper levels showed positive deviations at the end of

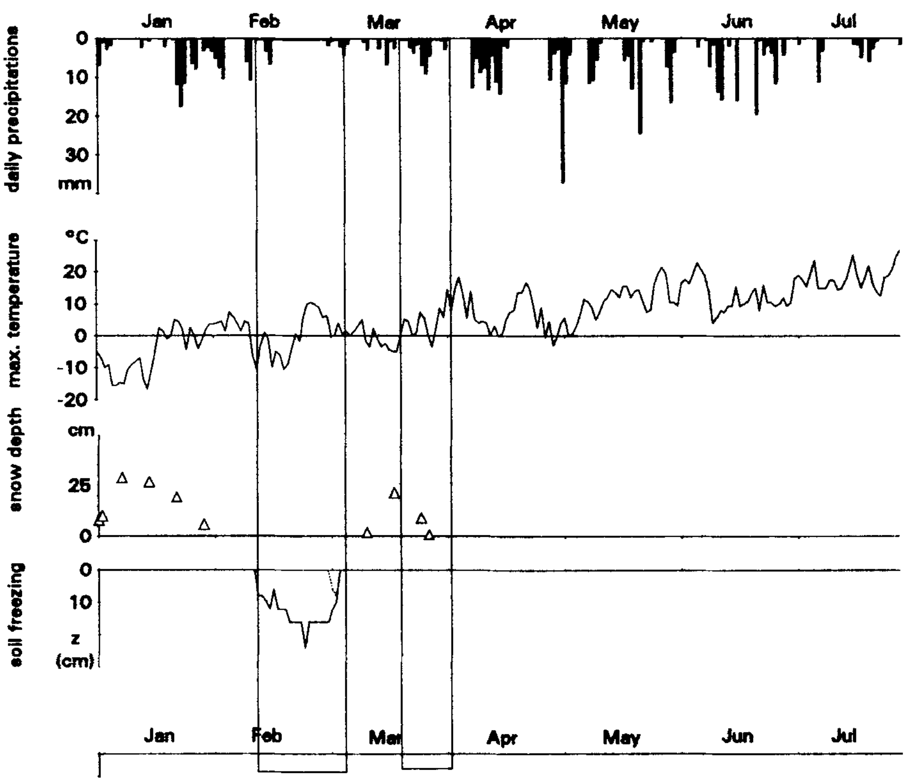

Figure 3. Climatic conditions during the study period

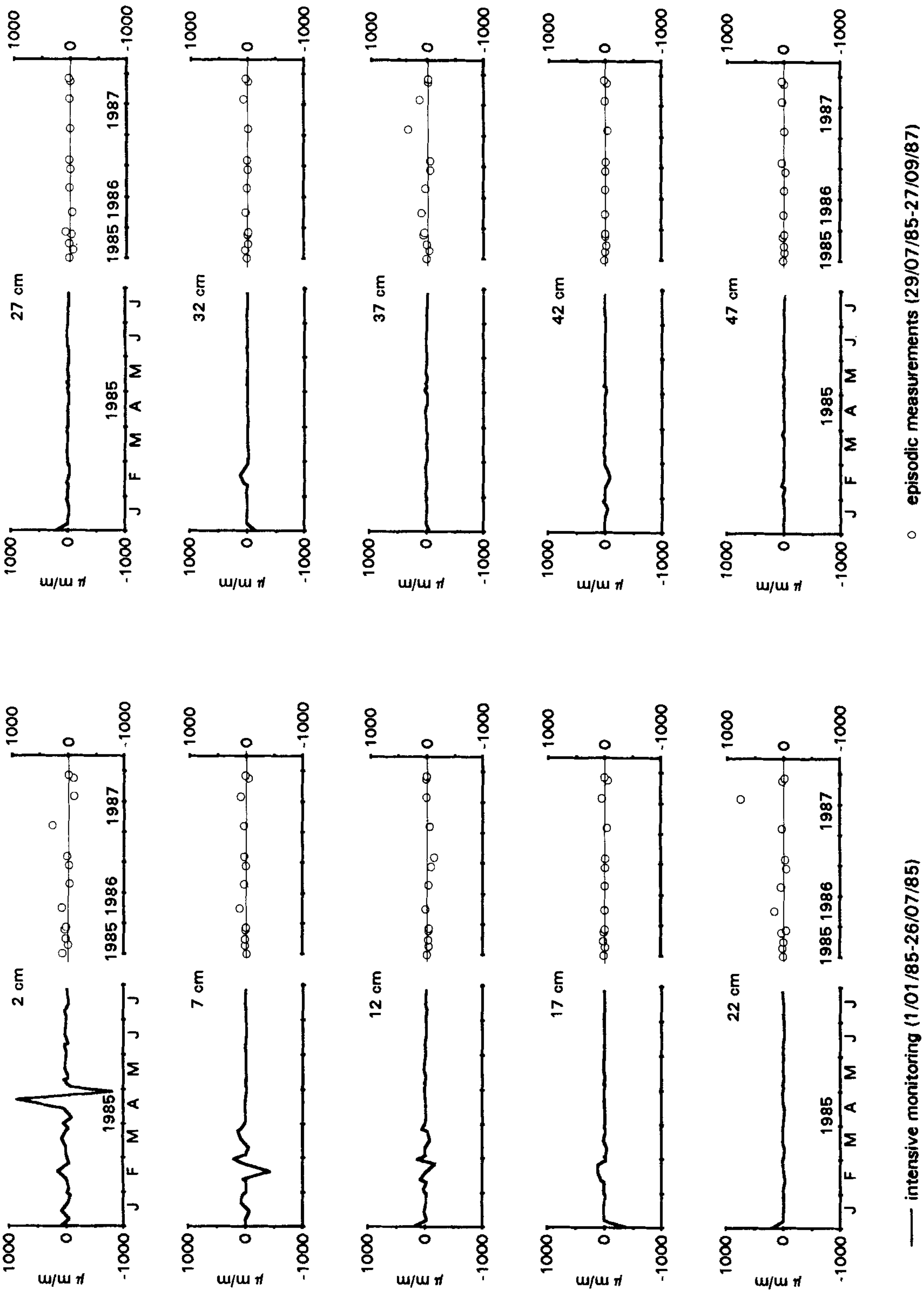

Figure 4. Time course of the strain gauge deformations

Table I. Soil creep displacements measured at the Schildmatt site

	Whole study period		Soil freeze–thaw		Snowmelt	
Depth (cm)	Mean (mm)	$\pm\sigma$ (mm)	Mean (mm)	$\pm\sigma$ (mm)	Mean (mm)	$\pm\sigma$ (mm)
Measured by the strain gauge probe at soil surface	2·9	0·4	10·2	1·0	1·9	0·6
2	2·5	0·4	9·1	0·9	1·4	0·5
7	1·8	0·3	6·0	0·8	0·8	0·4
12	1·0	0·3	3·3	0·6	0·6	0·3
17	0·8	0·2	2·0	0·5	0·3	0·2
22	0·2	0·2	0·8	0·4	0·1	0·1
27	−0·4	0·1	−0·3	0·2	0·0	0·0
32	−0·3	0·1	−0·3	0·2		
37	0·0	0·0	0·1	0·1		
42	0·0	0·0	0·0	0·0		
Measured by Anderson tubes of length L						
No. 1 ($L = 25$ cm)	2·5		2·4		−0·8	
No. 2 ($L = 15$ cm)	2·0		0·9		−0·8	
No. 3 ($L = 20$ cm)	1·4		1·9		0·4	
No. 4 ($L = 20$ cm)	2·0		4·1		−2·0	

March and the beginning of April: this period corresponds to the second snowmelt of the winter. The first level showed a positive deviation on 29 July, when intense rainfall occurred after a long, dry, hot period, causing rehydration and expansion. Nevertheless, some major climatic events, such as heavy rainfalls in November and at the end of April or the snowmelt in January, had no measurable effect.

The data for the previous changes were used to choose the dates for which the displacements could be calculated with some reasonable confidence. Most of them could be associated with specific moisture or temperature conditions. Nevertheless, and despite significant deformations according to the uncertainty estimation, some of them were difficult to interpret and should be considered, for the moment, to be random creep movements.

Effect of the soil freezing and thawing

There were two periods of intense frost, with negative daily maximum temperatures: from 24 December to 18 January and from 10 to 23 February. During the first one, the soil was protected by a snow cover and never froze; the strain gauge signals showed no significant change. During the second period, the snow cover was not continuous, negative temperatures were measured within the soil profile from 13 February to 3 March; the freezing front reached a maximum depth of 26 cm on 24 February.

This event had the greatest effect on the soil creep. The slow freezing of the initially very wet soil (Figure 5) fostered the development of ice lenses, as indicated by a large increase in the water tension. The ice lenses were probably randomly distributed at each level considering the high heterogeneity of the soil. There were significant changes in the strain gauge deformation down to 42 cm during the freeze–thaw cycle. They were the greatest for the four levels from 2 to 17 cm. The displacements were calculated between two dates before and after this freeze-thaw cycle.

The displacements at the soil surface over the whole freeze-thaw cycle was 10·2 mm (±1·0 mm) in the downslope direction. The displacements of the probe were noticeable down to the depth reached by the freezing front. Most were reversible: there was a relatively slow change in the reverse direction during March at all the levels where high deformations were measured during the freeze–thaw cycle. The partial reversibility of the displacements was also observed with the Anderson tubes (Table I).

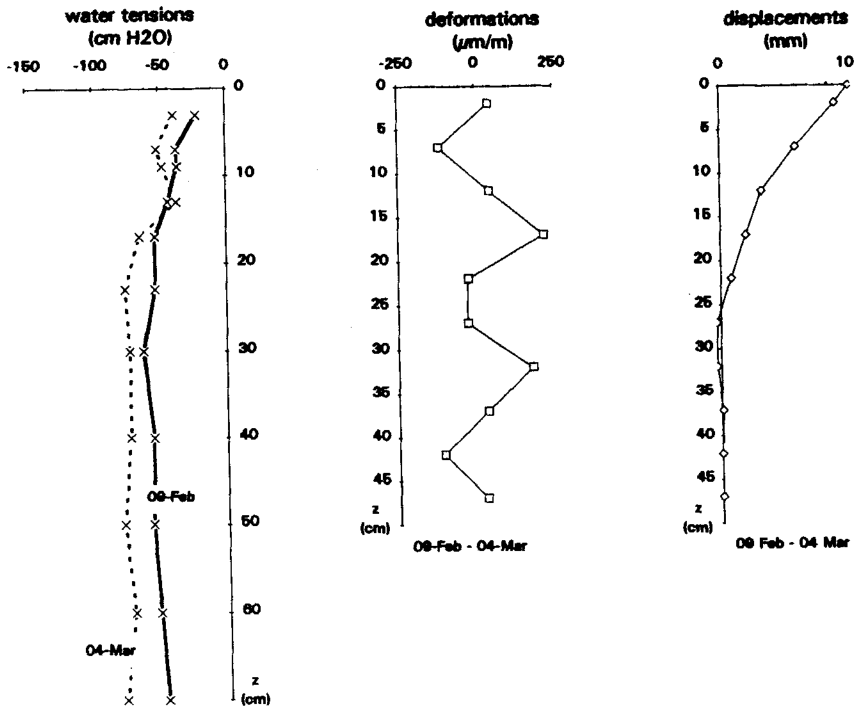

Figure 5. Changes during a freeze-thaw cycle (9 February to 4 March 1985)

Effect of snowmelt

Snow covered the soil twice during the winter of 1984–85: from 1 to 31 January and from 11 to 26 March. Its melting had very different effects on soil creep. In January, the snow cover was thicker (30 cm) than in March (20 cm), but the snowmelt had very little effect on the strain gauge signals, resulting in non-significant displacements. On the other hand, the snowmelt at the end of March caused deformations measured by three of the four upper stain gauge levels. The calculated displacement reached 1·9 mm at the soil surface (Table I, Figure 6). These differences between the two snowmelts were correlated with the change in the moisture conditions. The soil profile was near saturation at the end of the melt in both cases, but the initial conditions were very different (Figure 6). The snow that melted at the end of January had covered the soil since the end of December, and the soil profile was unsaturated at the beginning of the snowmelt (Figure 7), while in March the soil profile was very wet even at the beginning, and the quasisaturated conditions lasted until after the end of the melt (Figure 7). Water tensions were lowest at 17–23 cm, which is the limit between A_1B_h and B_h soil horizons.

Effect of rainfall

None of the three main rainfall events in November, April or June, resulted in significant displacements. Although they caused considerable wetting of the soil profile, they were probably not sufficiently intense or long-lasting. A storm with 12 mm of rain on 28 July (9 mm in 15 min) had an effect on the first level, but it was not large enough to result in any significant displacement. Taking into account the relatively great dryness of the whole soil profile prior to the rainfall, this change probably corresponds to a limited swelling of the previously dry organic layer. The wetting front reached a depth of only a few centimetres within the soil profile.

Overall displacements during the study period

The overall displacement calculated from the strain gauge measurements from January to July 1985 was

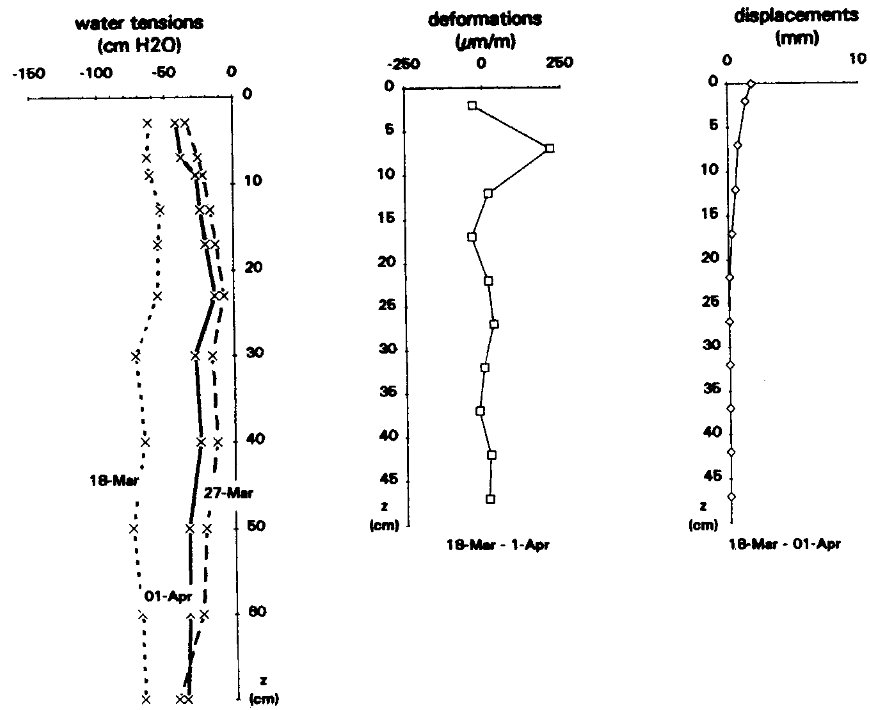

Figure 6. Changes during a snowmelt (18 March–4 April)

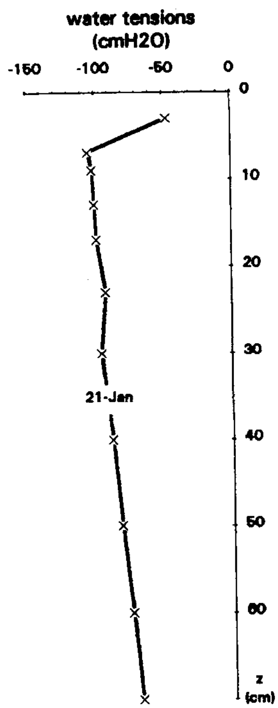

Figure 7. Water tension before the snowmelt at the end of January 1985

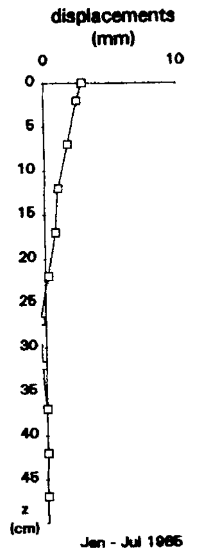

Figure 8. Change in soil creep profile throughout the intensive study period (January–July 1985)

3 mm at the soil surface (Figure 8). The mean displacement measured with the four Anderson tubes for the same period was 1·4–2·5 mm (Table I). These results are of the same order, considering, the accuracies of tubes and probes and the influence of local heterogeneousness. Anderson tubes tend to underestimate displacement: their size, rigidity and the density of the PVC, which is higher than that of organic layers, make them less sensitive than the flexible probes.

Even though many fewer measurements were made in 1986 and 1987, the deformations measured by the strain gauges showed the same trends (Figure 4); the greatest variations occurred during winters, especially during the winter of 1985–1986. Both winters were particularly cold, with long periods of freezing in February 1986 and January 1987, and limited snowfall. These conditions furthered the propagation of the freezing into the soil. Nevertheless, displacements were not calculated over these periods because measurements were not frequent enough to smooth out the random errors by averaging. During that period, the Anderson tube measurements were unfortunately no longer significant, because the PVC tubes were no longer cylindrical.

DISCUSSION AND CONCLUSION

The strain gauge probe developed for this study is able to monitor small deformations in the soil profile over short periods. These probes require careful construction, checking and data-processing, in order to separate significant deformations from errors. The main advantage is that it provides a dynamic approach to the deformation within the soil profile that can be correlated with soil moisture and temperature conditions.

The measurements made at the Schidmatt site emphasize the very discontinuous and reversible nature of the soil creep movements that affect mainly the upper layers. They confirm the results and assumptions made by Kirkby (1967) and Finlayson (1981). The overall displacement of 3 mm at the soil surface calculated from the strain gauge data is very similar to values measured by Anderson tubes and consistent with published creep rates for mountain slopes in the humid temperate zone. These overall displacements resulted from larger displacements (10 mm for the freeze–thaw cycle in February) in the downslope direction, followed by a smaller change in the opposite direction. Cumulative methods did not reveal the seasonal and episodic nature of the creep, which was most likely during short periods in winter.

The dependence of creep upon climatic events appeared clearly during the intensive study (January–July

1985) and was mainly the result of interactions between moisture and temperature conditions within the soil profile. Most of the displacements occurred in association with two events–a freeze–thaw cycle of the soil and a snow–melt–but other freeze–thaw cycles and snowmelt had no significant effect. The conditions within the soil profile before and during the events indicate that creep occurred only when the soil was initially very wet. Wet conditions during the freeze-thaw cycle fostered ice segregation. The importance of antecedent moisture conditions was also demonstrated by Coutard *et al.* (1988) for a loamy material. Initial very wet conditions seems to be a prerequisite for creep movements in coarse-textured soils with a high saturated hydraulic conductivity as at Schildmatt. The bottom of the creep displacements during the snowmelt corresponded to the bottom of the A horizons, where the water infiltration slows down. This result emphasizes the influence of the pedological stratification. More than the wetting and drying itself, which appeared not to be sufficient to promote creep movement in this type of soil profile, these observations suggest that very wet conditions lasting at least several days, with saturated conditions at a level, have a positive influence on soil creep.

The relationships between specific soil water and temperature conditions and the creep dynamics require further study in order to describe clearly the mechanisms themselves, particularly those that are influenced by water saturation and ice segregation in heterogeneous soils. This would enable changes in soil climatic conditions and net creep movement to be related, allowing estimation of long-term creep rates, which could be evaluated from the Schildmatt site and the same conditions at 2×10^{-4} to 3×10^{-4} m^3 a^{-1} (1×10^{-4} to 2×10^{-4} kg a^{-1}).

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